TEMPORALLY SHAPED CURRENT PULSES ON A TWO-CAVITY LINEAR TRANSFORMER DRIVER SYSTEM

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Abstract

An important application for low impedance pulsed power drivers is creating high pressures for shock compression of solids. These experiments are useful for studying material properties under kilobar to megabar pressures. The Z driver at Sandia National Laboratories has been used for such studies on a variety of materials, including heavy water, diamond, and tantalum, to name a few. In such experiments, it is important to prevent shock formation in the material samples. Shocks can form as the sound speed increases with loading; at some depth in the sample a pressure significantly higher than the surface pressure can result. The optimum pressure pulse shape to prevent such shocks depends on the test material and the sample thickness, and is generally not a simple sinusoidal-shaped current as a function of time. A system that can create a variety of pulse shapes would be desirable for testing various materials and sample thicknesses. A large number of relatively fast pulses, combined, could create the widest variety of pulse shapes. Linear transformer driver systems, whose cavities consist of many parallel capacitor-switch circuits, could have considerable agility in pulse shape.

We will show results from initial experiments in pulse shaping on a system with two inductively isolated cavities in series. Each cavity contains forty pairs of high voltage capacitors and forty gas-insulated spark gap switches. The capacitors are arranged in a bipolar configuration; the spark gap switches must withstand twice the capacitor voltage. A pulse applied to the switch trigger electrodes initiate closure of each switch. We have arranged triggering in groups of ten switches in each cavity, for a total of eight separate trigger points in the system. The fundamental rise time of each capacitor circuit is roughly 70 nanoseconds; this defines the fastest possible output pulse transition time. The pulse rise time can be made longer, and given features on the rise, by delaying triggers to some of the switches.

We will show initial experimental results from tests of the two-cavity system.

I. The cavity configuration

The linear transformer driver (LTD) cavities, trigger, and magnetic core reset systems used for these studies are units built by the Russian High Current Electronics Institute, to Sandia requirements. The cavities are each designed to deliver 1 MA into 0.1 Ω with ±100 kV charge voltage, and 100 kV output voltage. Because the output pulse is formed by magnetic induction, cavities may be stacked in series with the external housings at ground potential. In the present system, the two cavities in series would supply 1 MA into 0.2 Ω at full charge voltage. Each cavity contains 40 pairs of low inductance capacitors in a balanced plus-minus configuration, and 40 switches. The capacitors are rated for 100 kV; the switches are designed for 200 kV. The balanced charge configuration raises the output voltage of a cavity while maintaining the peak internal cavity potential to ground, allows the trigger electrode of the spark gaps to be at ground potential during charging, and eliminates a conductor that carries no net current that would exist between two unbalanced half-voltage cavities. The balanced configuration, however, doubles the potential that the high voltage switch must withstand prior to triggering. The cavities are meant to be stacked in an induction adder configuration, and contain ferromagnetic cores to minimize the shunt leakage current flowing in the metallic outer housing.

Figure 1 shows a cutaway view of the cavity design used. Each cavity of this type has 40 pairs of series capacitors and 40 spark gap switches. The capacitors are each 40 nF, resulting a total capacitance in the cavity of 800 nF. Each cavity can store up to 16 kJ. Because the 40 capacitor-switch circuits are in parallel, the inductance is lower than could readily be achieved with conventional pulsed power designs. The transit times within the cavity are much shorter than the characteristic pulse rise. The total cavity inductance is calculated here to be of the order 7.7 nH effective (this is in general agreement with Kim [1] who measured 7.15 nH). This implies 308 nH for each of the 40 capacitor and switch circuits. The $\sqrt{LC}$ time is therefore 78 ns. The system is ideally operated close to the matched impedance,

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14. ABSTRACT

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$\sqrt{\frac{L}{C}}$ [2], per cavity. In the present experiments, the load impedance was somewhat lower than matched for two cavities in series, at 0.11 Ω.

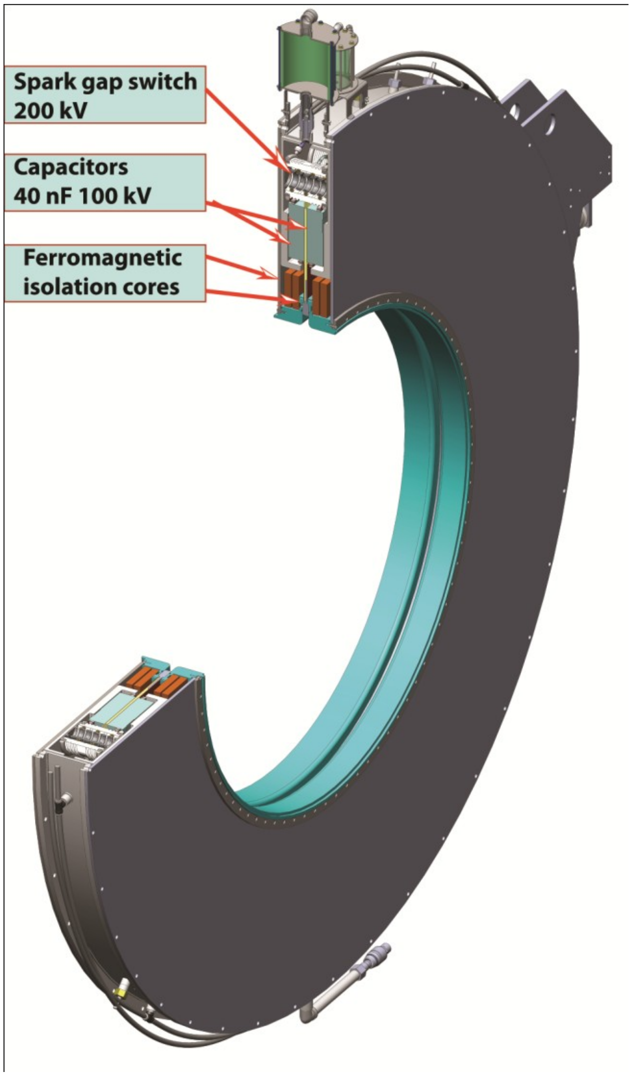

Figure 1. Cutaway view of a linear transformer driver cavity used for the pulse shaping experiment. Each cavity contains 80 capacitors and 40 switches, and stores 16 kJ at its full charge voltage. The outer diameter of the cavity is 3 meters.

A major application of large pulsed power facilities is material studies under dynamic loading. [3-9] Such applications use the magnetic pressure available from high current pulsed drivers. Very high currents are available from flux compression generators, but the nature of chemical explosives limits the fastest rise times (voltages) that are available from those devices. The fast characteristic times of purely electrical systems would allow wider bandwidth, manifested as faster rise times and transitions. In that vein, the Z machine at Sandia National Laboratories is presently used extensively for dynamic material studies. There, the 36 modules of Z are configured and timed independently to deliver 10 to 25 MA currents with current temporal profiles (which translates to the sample loading profile) optimized for reaching the desired pressures without shock formation in reasonably thick samples. The pulse shape flexibility allows high pressures without shock formation.

Because linear transformer drivers are comprised of a large number of parallel capacitor circuits added together, it is reasonable to consider pulse shaping with LTD systems. [10]

II. Experiment configuration

A system with two cavities was used for the initial proof of concept experiments. This LTD system has four separate trigger inputs for each cavity. Each trigger input controls ten switches. A water transmission line sums the output power from the cavities and carries the energy to a resistive load. The system is shown in Figure 2.

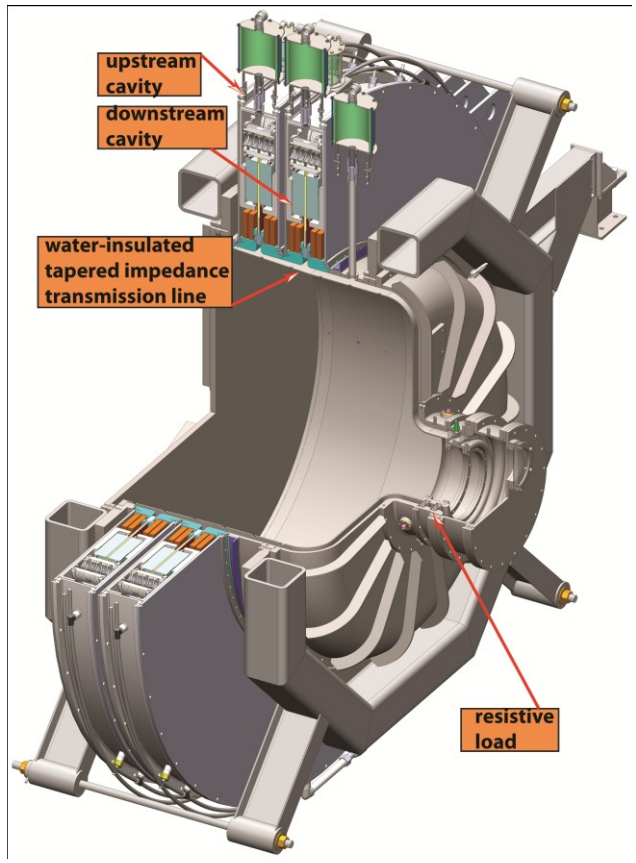

Figure 2. The two-cavity linear transformer driver system used for these experiments.

The ferromagnetic cores are reset by a low voltage pulse generator connected to the cavities only between shots with high voltage relays. An attempt was made to use inductive isolation instead of mechanical relays to protect the reset pulser from the LTD output pulse. Because the LTD output pulse is much faster than the reset pulse (~100 ns compared to 10 μs), inductive isolation is possible in theory. The amplitude difference between the reset pulse and the cavity output pulse, however, is large as well, and the reset pulser semiconductor switching devices can be damaged by ~500V transients. While an effective (but possibly elaborate) filter network could undoubtedly be built, the filter network tested was a simple series inductance combined with solid-state nonlinear surge suppressors. During testing, the solid-state switch and transient over-voltage devices in the reset generator were repeatedly damaged by the main LTD pulse when the reset pulser was connected to the triggered cavities. To address the failures, mechanical relays were added to isolate the reset pulser from the cavity output when the cavities were charged and triggered. The cavities are not even charged while the reset pulser is connected to the cavities, and the reset pulse generator has not failed since the mechanical isolating relays were installed. The cores are reset between pulses with a few kiloamperes of current flow in the opposite direction of the output pulse. This places the cores in the remnant flux density state, where the magnetization is zero ($B=-B_{remnance}$, $H=0$).

The notion of flowing reset current through the cavities during the cavity output pulse has been proposed. [1] The intent would be to place the cores at opposite saturation flux density instead of the remnant flux density, when the output pulse occurs. Resetting a ferromagnetic core to the saturation condition requires a pulse with both adequate duration and amplitude. [11] The increase in volt-second product from the cores set to the negative saturation condition would be significant (~25% for the core material used here) but the reset magnetization would have to meet or exceed the saturation value, which is 30 kA/m for the core material used. With the large diameter of these magnetic cores, the reset pulser would have to supply of order 150 kA. Given the complexity of such a high current reset generator, and the further issues of protecting the reset generator from the cavity output pulse, inter-pulse reset to the remnant flux density is used here, as is common on large induction adders. [12]

The capacitors in the cavities are charged through small (~1 cm diameter) copper sulfate solution resistors built from plastic tubing. The trigger isolation resistors are also made from copper sulfate solution in plastic tubing and are smaller (~3 mm diameter). Water permeates through the plastic tubing even when the resistors are submerged in transformer oil. We have measured water permeation rates of $3.5\times10^{-4}\,\frac{g}{cm^2\cdot day}$ with the plastic tubing we are using. Because the volume to surface area ratio decreases linearly with diameter, these small resistors have limited life in the system before the tubing collapses or bubbles form in the liquid volume due to the void left by the water that permeated through the walls.

The switches used in the system have been described previously. [13] The switches have multiple gaps graded by corona current. The multiple gap design makes the switches easier to trigger, because the first gap to be triggered is essentially at a fraction of the total switch voltage. Non-uniform corona current characteristics of the different corona needles could cause imperfect voltage grading and result in switch pre-fires. For this reason, the switches require conditioning shots before stable switch operation is achieved.

The switch trigger bus inside the cavity is normally azimuthally continuous. For these tests, we cut the trigger ring into four segments. The system then provides four discrete trigger points for each cavity. By inserting delay cables between the normal trigger cables and the cavity, pulse shaping can be tested on the system. With two cavities, a total of eight trigger points is available. The switches are triggered by application of a voltage comparable in peak amplitude to one side of the balanced switch voltage. The trigger signal flows in a 60Ω coaxial cable. Four such cables are used to trigger one cavity. The trigger bus is a small bare wire within the cavity, traversing the 90-degree segment. Each switch has a 1.5 kΩ trigger isolation resistor, so the effective load on the cable would be 150 Ω if the cavity capacitors were uncharged. However, since the side of the switch opposite in polarity to the trigger pulse will close first, the current will be higher. If the trigger amplitude is equal to the charge voltage, the current will double; this is the same as reducing the impedance by half. The effective trigger load is therefore about 75 Ω on each cable connected to ten switches, when triggering a charged system.

Pulse shaping by staggering switch triggers has some complications in this system. For intra-cavity pulse shaping (switches in a cavity closed at different times), the later switches to be triggered are at lower voltage at later times. This is because while the capacitor charge voltage on un-triggered switches is not changing appreciably, the cavity output voltage is increasing due to the early parts of the cavity. The dynamic voltage across the high voltage switches before triggering is $V_{switch}=V_0-V_{out}$, where V_{switch} is the voltage across the switch terminals, V_0 is the total capacitor charge voltage, and V_{out} is the cavity output voltage. When the switches are closed at the same time, V_{out} is zero when the switches are closed. A switch triggered later, however, operates with non-zero V_{out}, and so the switch voltage is lower (unless the output voltage reverses). The switch pressure has to be set properly to hold off the initial charge voltage. At the time of later triggering, the switch voltage is reduced, and the pressure is effectively higher than optimal. Later switches can thus be more challenging to trigger properly in intra-cavity pulse shaping.

In inter-cavity pulse shaping (timing variations between cavities), the situation is different. The voltage across later cavity outputs acts to increase the voltage on those later cavities. The exact amount of voltage increase depends on the distribution of the voltage from the early cavities. In a two-cavity system with a low impedance load, the peak voltage on the late cavity switches will be essentially doubled, unless the pulses are isolated by transit time.

The wave transit time between the cavities in the system shown in Figure 2 is approximately 6 ns. For times up to 6 ns between cavities, the cavity switch voltages are un-perturbed by other cavities. Since the pulse rise time of the cavities is 65 ns (10%-90%), total inter-cavity delays of 100 ns or more are needed to attain significant changes to the pulse shape. Notably, on the Z machine with comparable pulse rise times, inter-module times of 500 ns are common. With a small number of cavities (two in the present case), inter-cavity delay times much greater than the transit time between cavities are needed to affect the pulse shape. If the inter-cavity delay time is less than the full width of the output pulse, the switch voltages on late cavities is increased. If the voltage on the early cavities reverses, then the switch voltage on late cavities will be reduced after being increased. Because the over-voltage on late cavities is transient, the effect on the switch operation is less severe than would be a DC over-voltage. Such cases where the cavity switch voltage is increased are operationally more attractive, because the switch pressure can be set for the highest total voltage, which would be at the time of triggering. Very long inter-cavity delays would require, in the worst case, holding off the DC charge voltage, then being over-volted above the DC level, then triggered when the voltage is less than the initial charge voltage. With large numbers of cavities, the distribution of the early cavity voltages across multiple cavities reduces the effect, and with more cavities, less time difference between two nearby cavities would be required.

To the extent possible, it may be that inter-cavity pulse shaping is preferable in some cases. Systems with small numbers of cavities may be forced to use intra-cavity pulse shaping, just to have a large number of trigger points.

III. Experimental results

An experimental series was conducted on the two-cavity system to study the response of the spark gap switches to the dynamics of pulse shaping.

The system was used at ±80 kV charge voltage. Cavity quadrants were delayed by inserting lengths of cable between the common trigger generator and the quadrants to be delayed. The cables available ranged from 7.5 ns to 300 ns in single transit time.

The diagnostics consisted of current and voltage monitors at the load region. The monitors were derivative responding, and gave multi-volt signal levels. The signals were brought into a shielded room, attenuated, and recorded on digitizers sampling at 2 Gsamples/sec. The signals were numerically integrated after a gauge factor was applied.

The diagnostic monitors were calibrated using a 5 kA 100 ns rise time pulser. The voltage monitors were calibrated against a divider string made from 1 kΩ high voltage resistors.

The current monitors were calibrated against a Pearson 110A current monitor, which is accurate to ±1% absolute. For calibration, the current monitor signals were acquired with unity gauge factor. The signals were baseline-corrected, using hundreds of points of baseline to average and subtract any DC offset. The signals were then numerically integrated, and compared using an iterative routine to find the time shift and amplitude scale to minimize the point-wise rms differences between the reference waveform and the signal being calibrated. A number of refinement routines are available to process the data, including corrections for monitor frequency response, reference frequency response, water conductivity, ground loop noise, and magnetic field penetration. Using waveform points over the entire pulse of interest is the most effective way to calibrate wideband monitors. The signals, after some effort to tighten connectors and remove faulty components, gave rms point-wise deviations of a scaled signal divided by its peak of less than 1%. Tens of calibration tests were averaged to generate the gauge factors. The shot to shot variation in gauge factors was 0.3% or less. These variations are nearly ideal when using 8 bit digitizers.

For actual tests of the linear transformer system, the spark gap switches were set to the desired pressure, and the isolation cores were reset. The cavities were then charged, and the system was triggered. The digitizers were triggered by a reference voltage divider from a 20 kV thyratron pulser, which also triggers the master high voltage trigger generator. The master trigger generator is charged from the positive cavity power supply, so its output amplitude is constant relative to the cavity charge voltage. The master trigger generator has a single switch and 40 outputs for triggering ten cavities. The trigger output rise time with eight outputs in use is 140 ns. The rise time would degrade with more outputs connected. The forward going wave peak amplitude in the trigger cables is somewhat less than the positive charge voltage. The switch trigger electrode capacitance is less than 10 pF. With the 1.5 kΩ trigger resistors, the trigger RC time constant is 15 ns, which is much faster than the trigger pulse rise time. The trigger cables are shorter in transit time than the trigger pulse rise time.

Figure 3 shows load current with all switches triggered synchronously. The Figure also shows simulated load current. [14] The simulations assume 2 ns rms jitter switch normal distribution among the cavity switches, and the load impedance measured from the calibrated voltage and current monitors. The simulations use the Martin [15] arc discharge switch resistance model. The gas switches use dry air at 3 bar pressure; the gas type, pressure, and gap are all used in the switch model to calculate self-consistently the dynamic channel resistance.

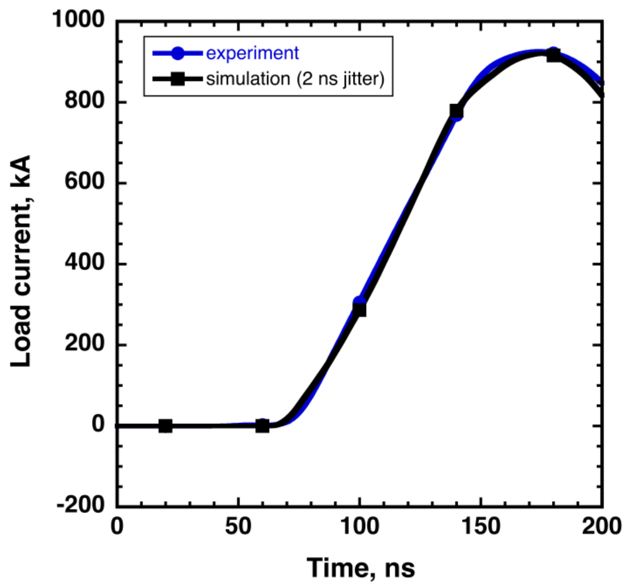

Figure 3. Load current with all switches triggered synchronously. A simulated current is also shown. The charge voltage was ±80 kV.

Figure 4 shows shaped pulse output for trigger delays in the range 15 to 75 ns. In all cases the earliest trigger had the normal trigger cable length; extra cable sections were inserted to delay some quadrants. In Figure 4, the curve labeled "intra-cavity only" used 45 ns delays to delay the entire upstream cavity. The curve labeled "inter-cavity only" shows results from a test with two quadrants of both cavities delayed by 45 ns from nominal. The curve labeled "6 trigger times" used a combination of intra-cavity delay with 0, 15, 30 and 30 ns delays to the downstream cavity quadrants, and 45, 45, 60, 75 ns delays to the quadrants of the upstream cavity.

Figure 5 shows measured load current with delays comparable to the pulse width. The "inter-cavity, 150 ns" curve shows the case with the upstream cavity delayed 150 ns. The measured delay between the pulse features is less than 150 ns because the later-triggered switches run faster, offsetting some of the inserted delay.

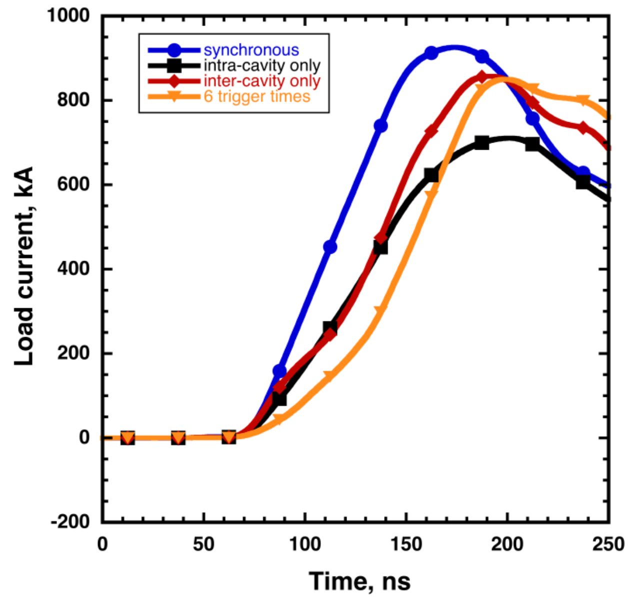

Figure 4. Pulse shaping with two cavities. The trigger delays were in the range 15 to 75 ns.

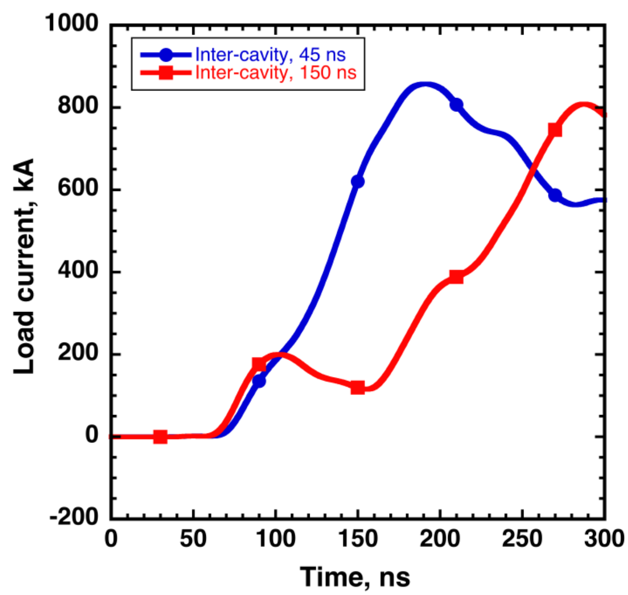

Figure 5. Pulse shaping with delay times comparable to the cavity rise time.

IV. Conclusions

We have shown results from preliminary pulse shaping experiments using a 1 MA fast linear transformer driver system. Using two cavities with four trigger inputs, we have eight separate trigger points in a system with 80 separate switches.

In these initial scoping experiments, the time to peak current of the composite output pulse was increased from 100 ns to almost 250 ns. Material scientists typically explore more extreme pulse shaping in pursuit of more accurate dynamic material data; larger temporal spreads in switch closure times are of interest. There are issues that become important for pulse shaping with trigger times varied over durations comparable to the pulse width. These issues are reduced switch voltage for later switches within a cavity (intra-cavity pulse shaping), and increased switch voltage on the switches in later cavities (inter-cavity pulse shaping).

The shaped currents produced are reproducible to a few ns in start time and a few percent in amplitude over the pulse.

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